THIRD GENERATION RLV STRUCTURAL SEAL DEVELOPMENT PROGRAMS AT NASA GRC

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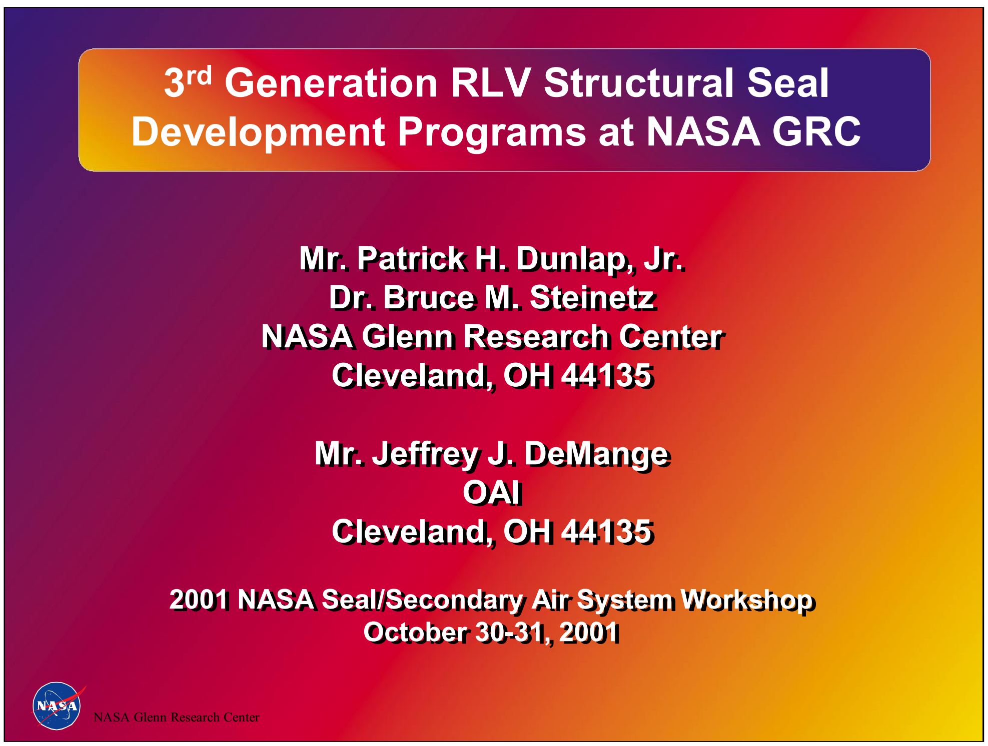
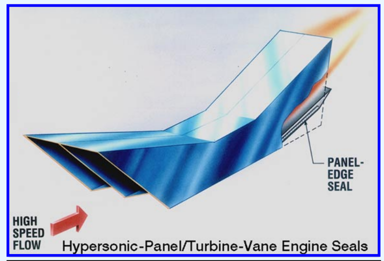
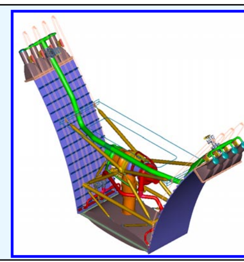


Background & History

- **NASA GRC is recognized as Center of Excellence for high temperature structural seal development:**
  - Led seal development effort for NASP (National Aero-Space Plane) project (1986-1992):
    - In-house propulsion system seal development program
    - Oversaw propulsion system seal development efforts at PW, Rocketdyne, & GE
    - Oversaw airframe and engine inlet seal development efforts at Boeing Phantom Works & Rockwell
  - Worked with Rocketdyne/Lockheed Martin on high temperature seal for linear aerospike engine ramps that accommodates large deflections (1998-2001)



NASP Propulsion System Seals



Linear Aerospike Engine

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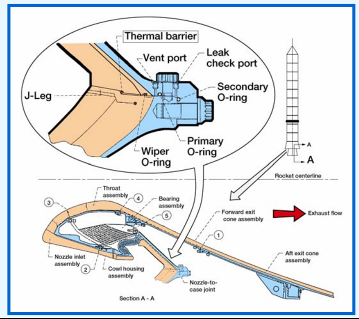
NASA GRC's work on high temperature structural seal development began in the late 1980's and early 1990's under the NASP (National Aero-Space Plane) project. Bruce Steinetz led the in-house propulsion system seal development program and oversaw industry efforts for propulsion system and airframe seal development for this vehicle. The figure at the upper right shows a propulsion system seal location in the NASP engine. The seals were located along the edge of a movable panel in the engine to seal the gap between the panel and adjacent engine sidewalls.

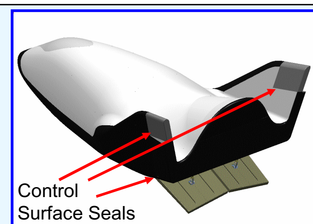
More recently, we worked with Rocketdyne on high temperature seals for the linear aerospike engine ramps. In applications such as the former X-33 program, multiple aerospike engine modules would be installed side by side on the vehicle. Seals are required in between adjacent engine modules along the edges and base of the engines, as shown in the figure on the lower right. The seals have to withstand the extreme temperatures produced by the thrusters at the top of the ramps while accommodating large deflections between adjacent ramps. We came up with several promising seal concepts for this application and shared them with Rocketdyne.

Background & History (cont.)

- Working with Thiokol/NASA Marshall to improve nozzle joint designs in Space Shuttle RSRM's. Thiokol is implementing more reliable J-Leg design and NASA GRC thermal barrier and eliminating joint-fill compound that can develop potentially damaging gas paths (1998-2001)
- Working with NASA JSC to develop and evaluate control surface seals (e.g., rudder/fin seals) for X-38/ Crew Return Vehicle (1999-2001)



Thermal Barrier for Shuttle RSRM



X-38 Seals

We have also been working with Thiokol over the past few years on improved nozzle joint designs for the Space Shuttle reusable solid rocket motors (RSRM's). Looking at the figure on the upper right, the seal location is where the nozzle bolts on to the bottom of the rocket. The current nozzle joint design uses RTV to seal the joints upstream of the O-rings. Occasionally though, gas paths can form in the RTV and focus hot gases on the O-rings. In an effort to solve this problem, Thiokol came to us to see if we had a seal that could be placed upstream of the O-rings. We came up with a braided carbon rope seal design that they are currently evaluating in as many as six of the nozzle joints as a way to overcome this problem and eliminate the RTV joint-fill compound.

We are also working with Don Curry and his group at JSC to develop and evaluate control surface seals for the X-38/Crew Return Vehicle. Don briefed these seal development activities earlier in the workshop.

Structural Seal Development Motivation and Objectives

- **Why is advanced seal development important?**
  - Seal technology recognized as critical in meeting next generation aero- and space propulsion and space vehicle system goals
  - Large technology gap exists in Hypersonic Investment Area for both control surface and propulsion system seals:
    - No control surface seals have been demonstrated to withstand required seal temperatures (2000-2500°F) and remain resilient for multiple temperature exposures while enduring scrubbing over rough sealing surfaces
    - No propulsion system seals have been demonstrated to meet required engine temperatures (2500+°F), sidewall distortions, and environmental and cycle conditions.
- **NASA GRC Seal Team leading two 3rd Generation RLV structural seal development tasks to develop advanced control surface and propulsion system seals**

Goal: Develop long life, high temperature control surface and propulsion system seals and analysis methods and demonstrate through laboratory tests.

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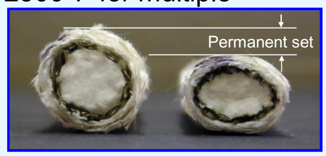
One might ask, “Why is advanced seal development important?” A large technology gap has been identified for both control surface and propulsion system seals. There are no existing control surface seals capable of withstanding required seal temperatures of up to 2500°F while remaining resilient for multiple heating cycles and enduring many scrub cycles over rough sealing surfaces. Also, there are no propulsion system seals that can endure engine temperatures as high as 2500+°F while sealing against distorted engine sidewalls in an extreme environment. These advanced seals are required for the next generation of aero-space vehicles. To fill this technology gap, the Seals Team at GRC has successfully advocated for two 3rd Generation RLV seal development tasks to come up with new, advanced control surface and propulsion system seals.

Control Surface Seal Challenges and Requirements

- **X-38 case study used to define seal requirements:**
  - Limit hot gas ingestion and leakage
  - Limit transfer of heat to underlying low-temperature structures
  - Withstand temperatures as high as 2000-2500°F for multiple heating cycles
  - Maintain resiliency (spring back) for multiple heating cycles
  - Limit loads against opposing sealing surfaces
  - Resist scrubbing damage against opposing sealing surfaces
  - Perform all functions for >10X increase in service life over current Shuttle seals



Challenge: Design hot, resilient seals that meet mission reusability requirements

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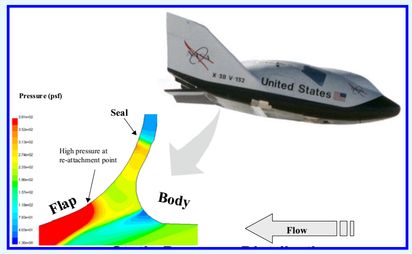
Now focusing specifically on control surface seals, this chart shows the challenges and requirements that new seal designs must meet. Because we have done a good deal of work in testing control surface seals for X-38, we are using these seals as a baseline upon which to improve. We are also using the X-38 application as a case study to define the requirements for advanced control surface seals. These seals must limit hot gas ingestion and leakage through the gaps that the seals are sealing to prevent the transfer of heat to low-temperature structures (including actuators) downstream of the seal. Gas temperatures that reach the seal can be as hot as 2500°F. The seals must be able to withstand these extreme temperatures and remain resilient, or “springy”, for multiple heating cycles. The image on this chart shows what happens to the X-38 seal design after exposure to 1900°F temperatures in a compressed state. The seals took on a permanent set and did not spring back to their original cross sectional shape. This can be a problem if the seal does not stay in contact with the opposing sealing surface and allows hot gases to pass over the seal and into regions where low-temperature materials reside. We are working on seal designs that would not have this problem and would remain resilient for many heating cycles. At the same time, the seals must not be too stiff so that they don’t impart excessive loads on to the structures that they are sealing against. The seals must also be resistant to wear as they are being scrubbed over the relatively rough sealing surfaces. The goal of this program is to develop seals that meet all of these requirements with a 10X increase in service life over the current seals used on the Space Shuttle that are replaced about every 8 missions.

Control Surface Seal Development Plans

- **Evaluate new control surface seal concepts under representative conditions (temperatures, pressures, scrubbing)**
- **New NASA GRC test rigs under development include:**
  - Hot compression rig (stroke rate: as low as 0.001 in/sec at 3000°F)
  - Hot scrub rig (stroke rate: up to 8 in/sec at 3000°F)
  - Cold flow/scrub test rig (ΔP: 0 to 2 psid)
- **Seal environmental exposure tests will be performed in other facilities:**
  - Arc jet tests to evaluate control surface seals (NASA Ames Panel Test Facility)
  - Thermal acoustic tests (NASA LaRC or WPAFB)
- **Aero-thermal-structural analyses of seals using tightly integrated CFD-FEA analysis tools**



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This chart shows how we are planning to develop our advanced control surface seals. We are coming up with new seal designs and plan to evaluate them in several new test rigs under representative conditions of temperature, pressure, and scrubbing. We are designing three new test rigs that we are going to install in our labs at GRC. The first two rigs listed, our hot compression test rig and hot scrub test rig, will actually use the same load frame and furnace with different test fixturing inside the furnace to perform the different tests. We have purchased a load frame from MTS and a box furnace from ATS. The furnace will be installed between the columns of the load frame and will be able to be heated to temperatures up to 3000°F. Test fixturing made of SiC will be used in different configurations inside the furnace to perform either compression or scrub tests.

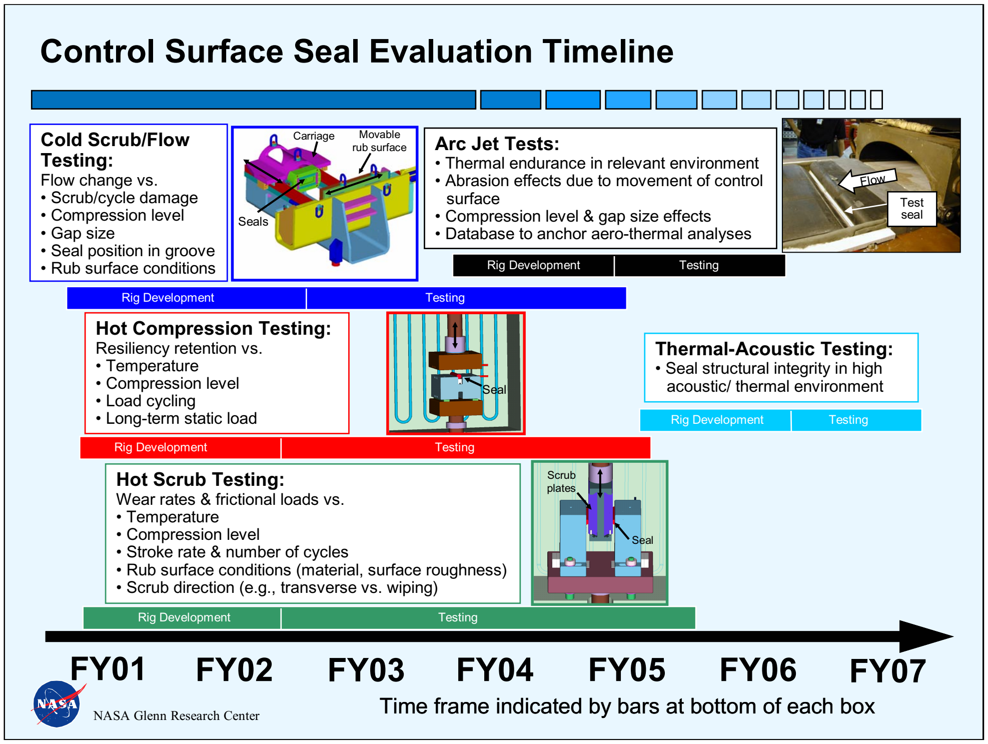
For the compression tests, the seals will be compressed between two plates and will be subjected to multiple compressive load cycles to generate load versus displacement curves for each cycle. We will be able to measure the resiliency, or spring back, of the seals at different temperatures for many load cycles. We will also be able to perform stress relaxation tests in which we load a seal at a given compression and see how the load falls off over time.

For the scrub tests, we will be moving a rub surface up and down in between two seals to scrub the seals against the surface for many cycles. We will monitor the friction between the seals and the rub surface and examine how the seals wear over time at different temperatures.

The other test rig we are developing will allow us to perform simultaneous flow and scrub tests on the seals at room temperature. We will be able to pass flow through the seals at the same time that they are being scrubbed against a moving rub surface to see how the flow blocking performance of the seals varies as they accumulate damage during scrubbing.

In addition to the tests rigs that we are building up for our lab at GRC, we also plan to perform tests at other facilities. Several years out, we plan to perform arc jets tests on our new seal designs at the NASA Ames Panel Test Facility. This facility produces extremely hot, re-entry-type gases that would pass over and impinge on the seals. This would simulate conditions that the seals would experience during re-entry. We also plan to evaluate our new seal designs in a thermal-acoustic facility either at NASA LaRC or at Wright Patterson AFB. These tests would expose the seals to both thermal and acoustic loads and evaluate their performance.

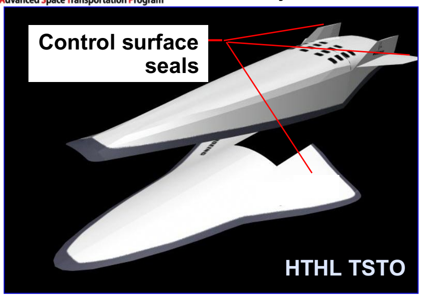
Finally, we are working with CFD Research Corp. to have them perform aero-thermal-structural analyses and develop models of our porous seal designs. We plan to use these models to predict temperatures and pressures that the seals would be exposed to as well as temperature drops across the seals that would be expected for a given seal configuration or design. These models will be validated against test data recorded in the flow, arc jet, and thermal-acoustic tests. The image at the lower right shows an example of the results that the thermal analyses would produce.



This chart shows a timeline for how and when we plan to have our rig development and testing occur during this program. Each rig and series of tests is color-coded so that an overall description and image of each test rig are shown above a bar indicating the time frame for rig development and testing. We are currently in the rig development stage for our new cold flow/scrub, hot compression, and hot scrub test rigs. We plan to begin hot compression and hot scrub testing by the summer of 2002, and we plan to have our cold flow/scrub test rig ready for testing by the fall of 2002. Further out on the schedule are the arc jet tests that we would do around FY05-06 and the thermal-acoustic tests that we plan to perform in FY06-07.

Exploring the Future
Advanced Space Transportation Program - *Airframe Project*

Advanced Control Surface Seals



Products / Benefits

Products

- Unique high temperature, robust control surface seals demonstrated in relevant laboratory environments (TRL-5)
- Arc jet tests and thermal acoustic tests database
- Validated seal aero-thermal-structural analyses

FY00/01 Accomplishments

- Preliminary arc jet control surface seal tests completed in Ames arc jet
- Seal concepts identified

Benefits

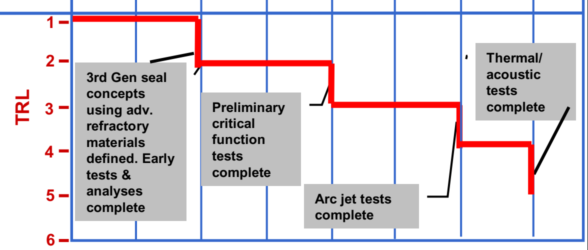
- Control surface seals able to sustain high heating rates (ascent and re-entry) and long cycle lives (10-100X Shuttle)

Customers: ASTP, X-37, X-38; all candidate Vision Vehicles

Implementation / Metrics

- **Performance Metric**
  - >10x increase in service life over Shuttle seals.
- **Risks**
  - Materials with inadequate performance capabilities
- **Future Plans (FY02 tasks)**
  - Seal aero-thermal-structural analyses
  - Unique performance test fixture fabrication
- **Participants: GRC Lead; Ames, WPAFB.**
  - POC: Dr. Bruce M. Steinetz, NASA GRC Bruce.Steinetz@grc.nasa.gov (216) 433-3302
  - POC: Mr. Patrick H. Dunlap, NASA GRC Patrick.Dunlap@grc.nasa.gov (216) 433-3017

FY	01	02	03	04	05	06	07	Tot
Current Prog. $M	0.500	0.420	0.420	0.420	0.420	0.420	0.420	3.02



This is the quad chart for our advanced control surface seal development task. The lower right hand corner of the chart shows our plan for TRL advancement over the course of this program. We are beginning at a TRL of one for the task and working up to a TRL of five by the end of FY07. At this point we will have tested the seals in a relevant laboratory environment.

Propulsion System Seal Challenges and Requirements

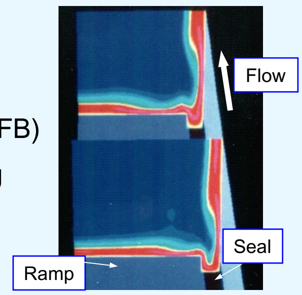
- **NASP and $\mathrm{I}^{\mathrm{STAR}}$ case studies used to define seal requirements:**
  - Withstand very high engine temperatures, as hot as 6000°F in combustor during scramjet operation
  - Limit leakage of hot gases and unburned propellant into backside cavities
  - Withstand chemically hostile environment
    - Oxidizing environment limits material selection
    - Hydrogen embrittlement can occur
  - Seal distorted sidewalls and remain resilient for multiple heating cycles ➨ flexible seals required
  - Survive hot scrub environment with acceptable change in flow rates
  - Utilize high temperature materials to minimize cooling requirements. Cooling schemes can be complex and heavy
  - Engine operation and mission safety demand highly reliable seals

Challenge: Design hot, flexible seals that require minimal coolant and meet engine life goals

Now let’s switch gears and discuss our other task for development of propulsion system seals. We used NASP and ISTAR seal case studies to determine our requirements for advanced propulsion system seals. Like the control surface seals, these seals must operate at very high temperatures and limit the leakage of hot gases into cavities behind the seals. In addition, propulsion system seals must prevent unburned propellant from getting into these cavities. If unburned propellant were to build up in a backside cavity it is possible that it could lead to an explosion. These seals must also withstand chemically hostile environments including oxidation and possible hydrogen embrittlement depending on the propellant. The seals must be flexible and resilient enough to conform to distorted sidewalls that they seal against and must endure scrubbing against these walls. To survive these extreme conditions, we plan to utilize high temperature materials to minimize the use of cooling schemes that can be complex and heavy. The seals must meet all of these requirements while operating safely and reliably.

Propulsion System Seal Development Plans

- **Evaluate new propulsion system seal concepts under representative conditions (temperatures, pressures, scrubbing)**
- **New NASA GRC test rigs under development include:**
  - Hot compression rig (stroke rate: as low as 0.001 in/sec at 3000°F)
  - Hot scrub rig (stroke rate: up to 4.5 in/sec at 3000°F)
  - Cold flow/scrub test rig (ΔP: 0 to 120 psid)
- **Seal environmental exposure tests will be performed in other facilities:**
  - Rocket heating/thermal survival tests to evaluate propulsion system seals (NASA GRC C-22 Rocket Facility)
  - Thermal acoustic tests (NASA LaRC or WPAFB)
- **Aero-thermal-structural analyses of seals using tightly integrated CFD-FEA analysis tools**



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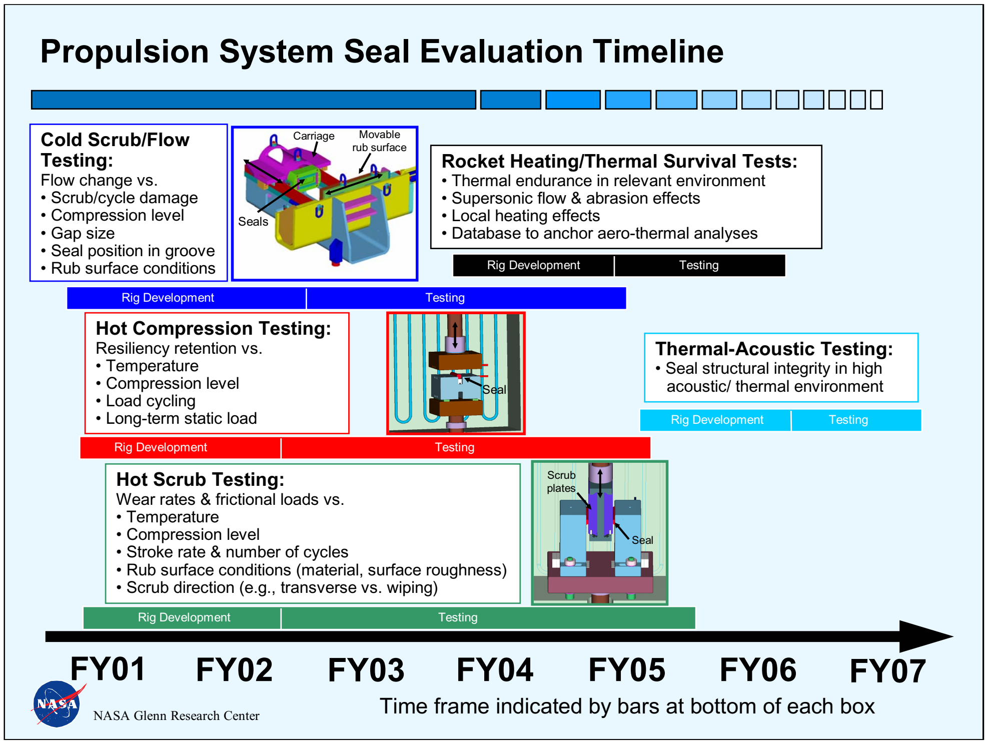
Like the control surface seals, we plan to come up with new propulsion system seal designs and evaluate them in our new test rigs. We plan to test these seals in the same test rigs but with different test fixturing than what is used for the control surface seals and under somewhat different pressure, temperature, and scrubbing conditions. One different test facility that we plan to test these seals in is NASA GRC's Cell 22 Rocket Test Facility. This facility will subject the seals to extreme thermal conditions similar to what they would experience in an advanced propulsion system. These tests will be performed in place of the arc jet tests that we will perform on the control surface seals. We also plan to perform a series of aero-thermal-structural analyses on new propulsion system seal concepts. An example of the results of such an analysis is shown in the lower right hand corner of this chart.

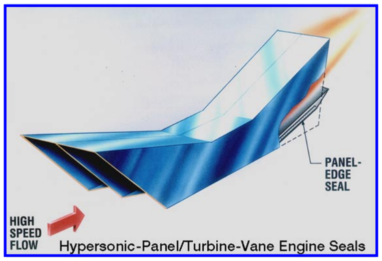


This chart is very similar to the one shown earlier for the control surface seals. The main difference is that the rocket heating/thermal survival tests are shown here in place of the arc jet tests that were shown for the control surface seals.

Exploring the Future

Advanced Space Transportation Program - *Propulsion Research & Technology Project*

Advanced Propulsion System Seals



RBCC or TBCC Inlet/Nozzle Ramp Seals

Products / Benefits

Products

- Long life, high temperature structural seals for propulsion systems demonstrated in relevant laboratory environments (TRL-5)
- Rocket heating/thermal survival tests and thermal acoustic tests database
- Validated seal aero-thermal-structural analyses

FY00/01 Accomplishments

- Seal concepts identified
- Customers identified: I^{STAR}, GTX

Benefits

- Dynamic structural seals able to sustain high temperatures (2000-2500°F) in propulsion system environments for many engine cycles

Customers: ASTP, I^{STAR}, GTX; Vision Vehicles: all RBCC/TBCC powered vehicles

Implementation / Metrics

- **Performance Metric**
  - Maximum seal temperature of 2000-2500°F
- **Risks**
  - Materials with inadequate performance capabilities
- **Future Plans (FY02 tasks)**
  - Seal aero-thermal-structural analyses
  - Unique performance test fixture fabrication
- **Participants: GRC Lead; WPAFB.**
  - POC: Dr. Bruce M. Steinetz, NASA GRC Bruce.Steinetz@grc.nasa.gov (216) 433-3302
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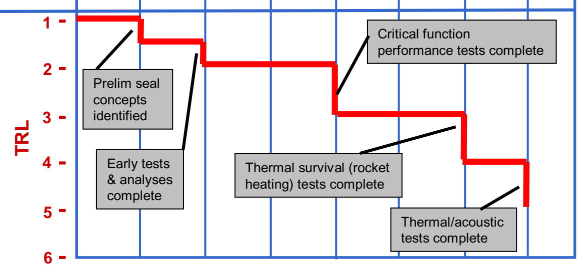
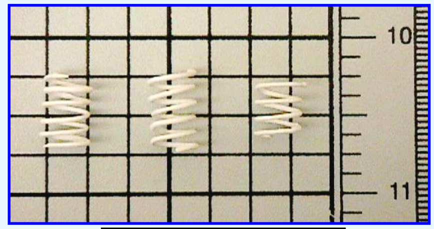
FY	01	02	03	04	05	06	07	Tot
Current Prog. $M	0.398	0.400	0.400	0.400	0.400	0.400	0.400	2.798



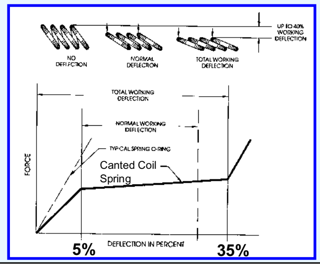
This is the quad chart for our advanced propulsion system seal development task. Like the quad chart shown earlier, the lower right hand corner of this chart shows our plan for TRL advancement over the course of this program. We are beginning at a TRL of one for the task and working up to a TRL of five by the end of FY07. At this point we will have tested the seals in a relevant laboratory environment.

Ceramic Canted Coil Spring Development: Seal Preload Device

- **Established grant/cooperative agreement with Case Western Reserve University to develop high temperature (up to 2500°F) seal preload methods (i.e., ceramic canted coil spring)**
- **FY01 Accomplishments**
  - Formulated extrudable mixture of raw materials to create YAG ceramic prototype springs (material not fully dense)
  - Currently pursuing alternative methods of producing YAG to improve density/reduce porosity of parts
  - Fabricated laboratory-scale extruder
  - Setting up equipment for winding mechanism
- **Phase I of multi-phase program**



Prototype YAG springs



Typical deflection curve for canted coil spring: provides large working deflection

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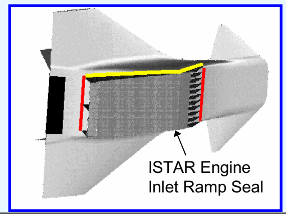
This chart highlights one of our accomplishments for our seal development tasks over the past year. In an effort to develop a new method of preloading our seals, we established a cooperative agreement with Case Western Reserve University to have them develop canted coil springs out of ceramic materials. Ceramic tension and compression springs do exist, but we are not aware of any ceramic canted coil springs that are being produced. Canted coil springs are different from regular tension or compression springs in the direction that they are loaded. Tension and compression springs are typically loaded in a direction parallel to a line down the center of the spring. Canted coil springs, though, are loaded across the coils as shown in the figure on the bottom right of this chart. They can be produced in long lengths that would be laid in a groove behind a seal to provide additional resiliency, or spring back, to the seals. Another unique feature of these springs is that as the coils of the spring deflect under a load, the force produced by the spring on the opposing surface stays rather constant over a broad range of deflections. This produces a force vs. deflection curve that is close to flat as shown in the figure at the lower right. This would be a beneficial feature for the seals because it would provide resiliency to the seals without producing excessive loads against the opposing sealing surface.

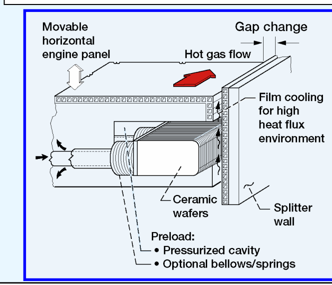
Over the past year CWRU has formulated an extrudable mixture of raw materials to produce YAG filaments that can be wound into prototype springs, as shown in the figure at the upper right. The material that they are producing is not fully dense, though, so they are pursuing alternative methods of producing YAG to improve the density and reduce the porosity of the parts. They have fabricated a laboratory-scale extruder to extrude this material and are currently setting up the equipment for a winding mechanism. This is all part of Phase I of a multi-phase program.

Summary of Significant FY01 Accomplishments

- **Identified customers for both programs**
  - Control surface seals: X-38/Crew Return Vehicle, X-37
  - Propulsion system seals: I^{STAR}, GTX, other RBCC/TBCC-powered vehicles
- **Baseline Shuttle seals evaluated for X-38 control surface seal applications**
  - Performed baseline compression, flow, scrub, and arc jet tests
  - Arc jet database to be used to validate aero-thermal-structural analyses codes to predict seal loads for future mission conditions
  - Lessons learned form basis for advanced control surface seal development program
- **New control surface and propulsion system seal concepts identified**



ISTAR Engine
(P&W/Aerojet/Boeing/Rocketdyne)



Propulsion system seal concept

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In addition to setting up the cooperative agreement with CWRU, we have had many other accomplishments over the past year. We have identified customers for both programs: X-38/Crew Return Vehicle and X-37 for the control surface seals task and ISTAR, GTX, and other RBCC/TBCC-powered vehicles for the propulsion system seals task. We evaluated control surface seals for the X-38 through compression, flow, scrub, and arc jet testing and are using the results of these tests as a baseline upon which to improve in our advanced control surface seal development task. Data from the arc jet tests will be used to validate aero-thermal-structural analyses codes to predict seal performance for future mission conditions. Finally, we have come up with new control surface and propulsion system seal concepts that we plan to evaluate in the new test rigs that we are developing. A drawing of one of the propulsion system seal concepts is shown at the lower right of this chart.

Summary of Significant FY01 Accomplishments (cont.)

- **New performance test fixture acquisition/fabrication:**
  - Test cell cleared out in preparation for new rig installations
  - Hot compression/hot scrub test rig:
    - Main elements of test rig (load frame, furnace, and laser extensometer) ordered and being delivered
    - Preliminary designs for high temperature test fixturing complete
  - Cold flow/scrub test rig:
    - Ordered and received many commercial parts for test rig (e.g., drive mechanism, instrumentation)
    - Preliminary design of fabricated parts (e.g., weldments, seal cartridges) complete. Detailed design underway.
- **Contracted with CFD Research Corp. to perform aero-thermal-structural analyses of gap seals operating in high Mach environment. Currently calibrating models including porous seals using data recorded in arc jet tests at Ames**

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We have also been working on the new test rigs that we are planning to use to evaluate our new seal designs. For our hot compression/hot scrub test rig, we have ordered the main elements of the test rig (load frame, furnace, and laser extensometer) and are assembling and installing them as they are delivered. We have completed preliminary designs for the high temperature test fixturing that we are going to use inside the furnace for these tests. For the cold flow/scrub test rig, we have ordered and received most of the commercial parts for the rig. The preliminary design of the fabricated parts for the rig is complete, and we are currently working on the detailed drawings for these parts.

We contracted with CFD Research Corp. to perform the aero-thermal-structural analyses on the seals that were discussed earlier. Alton Reich from CFD RC will be briefing the progress on these analyses in a later presentation.